Bio-Inspired Engineering of Exploration Systems

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Abstract

This paper describes the multidisciplinary concept of Bio-inspired Engineering of Exploration Systems (BEES) and the new terminology associated with this concept. BEES utilizes small, dedicated, low-power, and low-cost "biomorphic explorers" that capture selected functional traits of biological systems with the goal of obtaining 'leap-frog' advances over existing mobile robotic systems and enabling cooperative "biomorphic missions." Biomorphic explorers can empower a reach and sensory acquisition capability from otherwise hazardous and/or inaccessible locations. Biomorphic missions are cooperative missions that make synergistic use of existing and conventional surface and aerial assets, such as landers, rovers and orbiters, along with biomorphic explorers. Just as in nature, where biological systems offer a proof-of-concept of symbiotic coexistence, the intent here is to distill some of the key principles and success strategies demonstrated by nature and capture them in our biomorphic mission implementations. Specific science objectives targeted for these missions include close-up imaging for identifying hazards and slopes, assessing sample return potential of target geological sites, atmospheric information gathering by distributed multiple-site measurements, and deployment of surface payloads such as instruments or surface experiments. A few candidate biomorphic mission scenarios are also described.

I. INTRODUCTION. Space exploration presents the daunting and expensive challenge of reaching to the unknown uncharted planets. Be it for exploring new planets for NASA or dealing with the needs of DoD, such as surveillance of unfriendly or hazardous territories, the challenge is to deal with unpredictable situations or environmental conditions and to have the versatility of adapting to unknown and unanticipated situations. Advanced robotics, in spite of all the recent engineering advances, remains short on capabilities with respect to agility, adaptability, intelligent sensing, fault-tolerance, stealth, and utilization of in-situ resources for power compared to some of the simplest biological organisms. The multidisciplinary system concept of Bio-inspired Engineering of Exploration Systems (BEES) described in this paper utilizes small, dedicated, low-power, and low-cost biomorphic explorers that capture selected functional traits of biological systems to obtain leap-frog advances over existing mobile robotic systems. The biomorphic systems so enabled can range from insectoids to humanoids.

The general premise of bio-inspired engineering is to *distill* the principles incorporated in successful, nature-tested mechanisms of selected features and functional traits that can be enabling to new endeavors; *capturing* the biomechatronic designs and minimalist operation principles from nature's success strategies. The intent is not just to mimic operational mechanisms found in a specific biological organism, but to imbibe the salient principles from a variety of diverse bio-organisms that employ differing manifestations to achieve a specific function, thus capturing the key functional traits of interest for that specific functionality as multiple tool options in the artificial system that we build. Such features include versatile mobility (e.g., burrowing, soaring), adaptive controls, agile and stealthy response, bio-inspired sensor mechanisms, sensor fusion, biomorphic communications, and biomorphic cooperative and distributed operations. This approach will allow building systems that have specific capabilities endowed beyond nature as they will possess a mix of the best tools from nature for that particular function.

The major subsystems breakdown of BEES and major categories therein are highlighted in Figure 1.

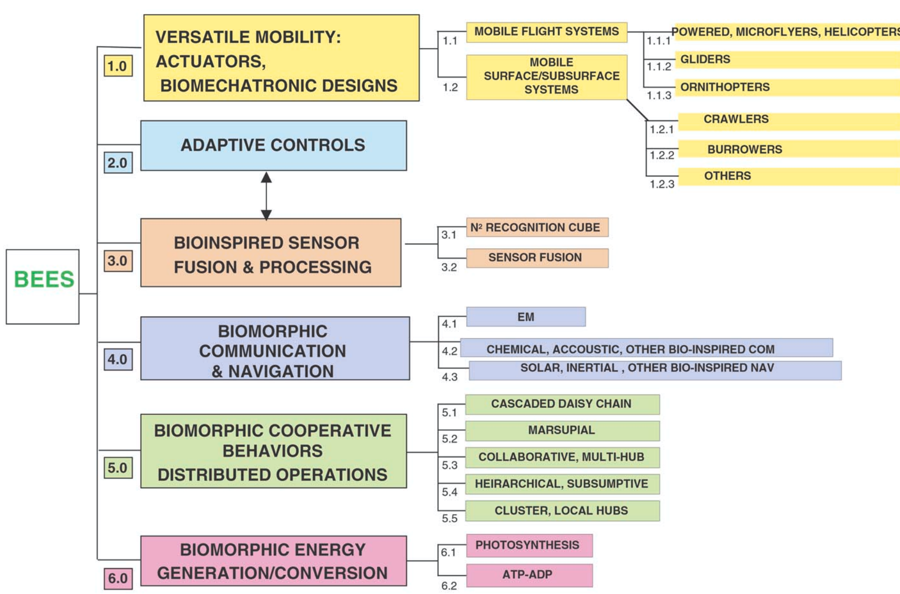

Figure 1. Subsystem breakdown for BEES

Biomorphic Explorers

Biomorphic explorers embody a unique combination of versatile mobility controlled by adaptive, fault-tolerant, biomorphic algorithms with the ability to autonomously match the changing ambient/terrain conditions. Significant scientific payoff at a low cost would be realized by using the potential of a large number of such cooperatively operating biomorphic systems. Biomorphic explorers can empower the human to obtain extended reach and sensory acquisition capability from otherwise hazardous/inaccessible locations. A classification of such explorers, with example candidates in each category, is illustrated in this paper. The biomorphic flight systems are extremely attractive for solar system exploration because of their potential large range, unique imaging perspective, and the access they would provide to heretofore inaccessible sites.

Biomorphic Missions

Biomorphic missions are cooperative missions that make synergistic use of existing and conventional surface and aerial assets, such as landers, rovers, and orbiters, along with biomorphic explorers. Just as in nature, biological systems offer a proof-of-concept of symbiotic co-existence. The intent here is to distill some of the key principles and success strategies demonstrated by nature and capture them in our biomorphic mission implementations. Specific science objectives targeted for these missions include close-up imaging for identifying hazards and slopes, assessing sample return potential of target geological sites, atmospheric information gathering by distributed multiple-site measurements, and deployment of surface payloads such as instruments or surface experiments. A few candidate biomorphic mission scenarios are also described.

II. Classification Of Biomorphic Explorers. Figure 2 illustrates examples of natural biological systems that have inspired the design of biomorphic explorers. Pick a feature, such as soaring. The intent is to make an explorer that combines different attributes seen in diverse soaring species and capture many of them in one artificial entity, to go beyond biology and achieve the unprecedented adaptability needed when encountering and exploring what is as yet unknown. As another example, consider the trait of "subsurface burrowing." This is observed in species as diverse as a germinating seed, an earthworm, and *Amphisbaenia,* a generally legless order of reptiles that creates tunnels by forcing themselves through the soil. A burrowing platform that would imbibe the characteristics of burrowing in a multifaceted way (like a Swiss army knife), capturing the burrowing capability of each of those diverse bio-species, is needed to address the challenge offered by a range of NASA and DoD applications. For example, very little is known about the soil conditions and their variability on Mars. To realize the goal of looking for water, a biomorphic explorer is needed that can adapt to multiterrain, particularly subterranean, conditions.

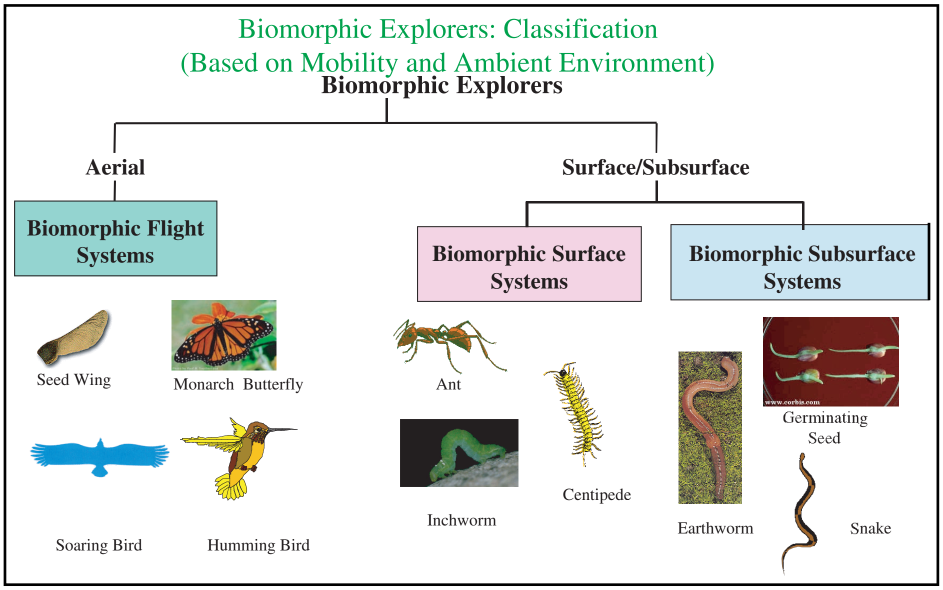

Figure 2. Examples of biological inspiration in different mobility categories

These examples of inspiration are classified into subdivisions of aerial systems and surface/subsurface systems based on their mobility type and environment.

Biomorphic explorers may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and aerial exploration. They would combine the functions of advanced mobility and sensing with a choice of electronic and/or photonic control. Pre-programmed for a specific function, they could serve as one-way communicating beacons, spread over the exploration site, autonomously *looking for and at the targets of interest*. In a hierarchical organization, these biomorphic explorers would report to the next level of exploration mode (say, a large conventional rover) in the vicinity. This would allow a widespread and affordable exploration of a new/hazardous area at lower cost and risk, with a substantial amount of scouting for information. It also allows for combining a fast-running rover to cover long distances with the deployment of numerous biomorphic explorers for distributed sensing and local sample acquisition.

III. Biomorphic Explorers—A New Paradigm In Mobility. Figure 3 illustrates the key points of the new paradigm, taking an example from the surface systems.

A quick response to even an unanticipated sensory stimulation and adaptation of the prevalent mobility style to suit changing environment/ambient conditions occur naturally in biological organisms—in striking contrast with respect to existing artificial mobile systems. This is primarily due to the basic differences between the naturally evolved "controls" in bio-organisms that smoothly "transform" the sensory inputs (n)

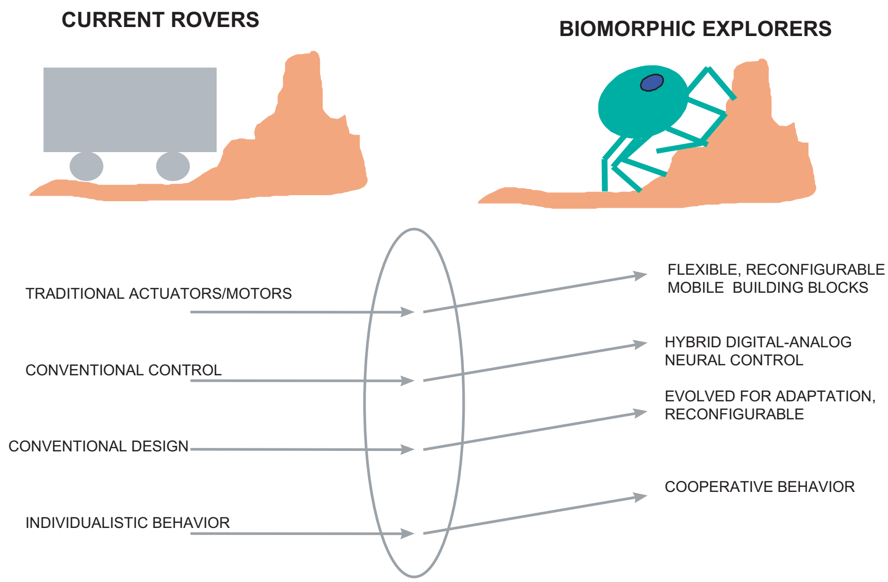

Figure 3. Mobility: New paradigm

into the actuator outputs (m) and the human-engineered, mathematically rigorous controls, captured in discrete functions, typically optimized for a given system architecture, with limited adaptability. These differences are summarized in Table 1.

Earlier work on biologically inspired robots was done in many different parts of the world (Robot Development 1989–2000). Biomorphic explorers, the new paradigm in mobility (Thakoor and Kennedy 1998; Thakoor and Stoica 1998) that we describe here, combines bio-inspired versatile mobile units and adaptive control to capture key features and mobility attributes of biological systems that are of interest for specific applications. Biomorphic explorers (Background 1998–2000) are a

Table 1: Comparison of Biological Systems with Existing Artificial Mobile Systems

Biological Systems	Existing Artificial Mobile Systems
“Live off the land”	Usefulness limited by battery life and size
Complex correlation embedded in transformation	Simple rule-based look-up tables
Continuous, n is large	Typically n < 10
Adaptable, learning capable	Rule based, fixed
Response agile, smooth	Response jerky, discrete
Muscle actuators, organic	Motors, inorganic actuators

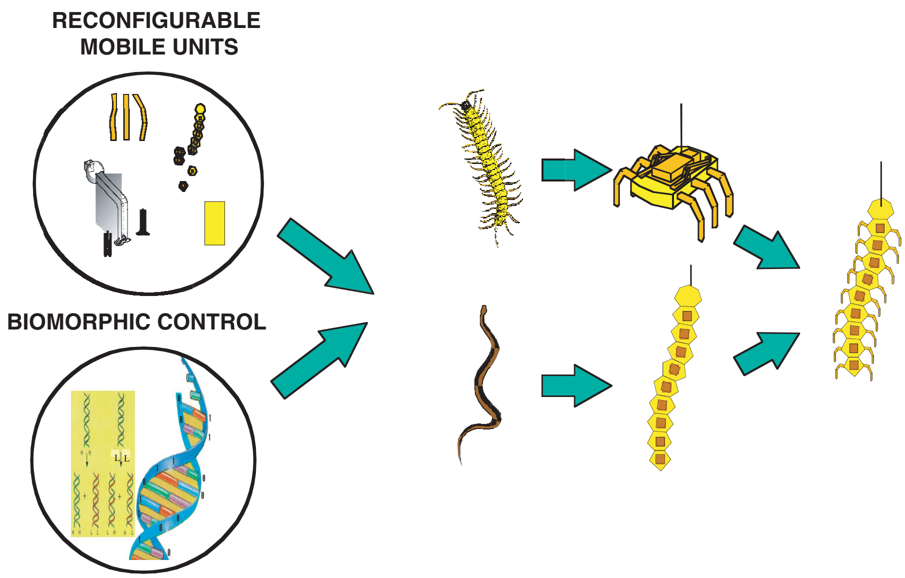

Figure 4. Schematic illustration of the concept of biomorphic explorers

unique combination of versatile mobility and control by adaptive, fault-tolerant biomorphic algorithms designed to autonomously match with the changing ambient/terrain conditions. This represents the movement from rigid, mobility-limited traditional robotics to adaptive, biomorphic explorers. Important features of the paradigm shift, illustrated in Figure 4, are discussed in the following.

Features

1. Advanced reconfigurable mobile units will allow design of direct-driven limbs, bypassing the need for complex chassis (drive systems). These limbs will possess the versatility of configurations within a certain domain of mobile systems.
2. Inspired by biology, biomorphic controls (based on the artificial neural network (Daud et al. 1995; Webb 1996) implemented in low-power VLSI hardware) would be especially suited for controlling the inherently non-linear mobility attributes.
3. Revolutionary mechanisms for adaptation would replace traditional fixed designs. For example, sensor-triggered control sequences to the legs may be determined for optimal ways to move in various different environmental conditions.
4. In addition, inspired by the ability of insects to hone in on targets using thermal and chemical sensors, and their unique communication abilities, cooperative behavior (Thakoor 1997; Thakoor 1998b; Thakoor et al. 1999) among many such explorers would enable new types of missions. Using groups of biomorphic explorers in conjunction with larger, traditional mobile robots will enable tasks too complex for a single robot.

Table 2 compares the new approach to conventional robots with conventional controls and conventional robots with biomorphic controls.

Biomorphic explorers offer the potential to obtain significant scientific payoff at a low cost by utilizing the power of a large number of cooperatively functioning units. This is analogous to the approach seen in insect societies.

Recent NASA studies (Thakoor 1997; Thakoor 1998b; Thakoor 1999b) suggested that biomorphic explorers could be feasible and cost-effective. An important application would be to use them as scouts in future planetary exploration, where they would look for samples/sites of interest. Inspired by the world of insects and animals, the well-proven natural 'explorers' on this planet, biomorphic explorers represent an exciting alternative to traditional, labor-intensive, telerobotic operations. The studies concluded that combining flexible, reconfigurable mobile units

Table 2: Comparison of Conventional Approaches and the Biomorphic Approach

	Conventional Robots with Conventional Controls	**Conventional Robots with Biomorphic Controls**	**Biomorphic Explorers with Biomorphic Controls**
Actuator Shape	Wheels (legs, experimental)	Wheels (legs, experimental)	Any shape (legs, limbs) modifiable
Actuator Type	Conventional actuator materials, mostly rigid	Conventional actuator materials, rigid	Novel flexible actuators (low power, mass, and volume)
Drive Mechanical Motion	Electrical motors, complex transmission	Electrical motors, complex transmission	Direct-driven flexible actuators
Control Strategy	Control rules based on terrain models	Learning, adaptive, neural (biomorphic) controls	Learning, adaptive, neural (biomorphic) controls reconfigurable
Control Sequence	Predetermined, Designed	Adaptively evolvable, generalizable	Adaptively evolvable, generalizable and reconfigurable
Terrain Adaptability	No	Partial, limited by actuator type, rigidity	Yes
Fault Tolerance	No	Partial, limited by actuator type, rigidity	Yes
Scale Independent, Miniaturization	No	No	Yes
Spatial Access, Narrow Crevices	No	No	Yes
Ratio: Complexity or Cost/ Capability	High	High	Low

and biomorphic controls would offer, for the first time, the possibility of autonomous exploration with adaptation to varying terrain conditions. Figure 5 shows (on the left-hand side) examples of reconfigurable mobile systems found in nature in the surface mobility and aerial mobility domains. These systems are specifically suited to their environments and functions. Corresponding examples of artificial biomorphic systems that are in the design process currently at JPL (Thakoor and Kennedy 1998; Thakoor and Stoica 1998; Background 1998–2000) or elsewhere (Yim 1998) are shown on the right-hand side of Figure 5. Biomorphic explorers could provide enhanced spatial access and ease of production with low recurring cost, due to their simple design. This level of autonomous exploration would be beneficial to several planetary science goals. These goals include: scouting for conditions compatible with life (to lead us to the right spots that may hold samples of extinct/extant life); in-situ sensing to obtain physical, meteorological, and chemical data on unexplored planetary surfaces; and the investigation of previously inaccessible locations. On Earth, biomorphic explorers would offer new capabilities for exploration, surveillance, advanced warning systems, and access to difficult environments.

In-situ, autonomous exploration and science return from planetary surfaces and subsurfaces would be substantially enhanced if a large number of small, inexpensive, and therefore dispensable biomorphic explorers equipped with dedicated microsensors could be spread over the surface by a lander or a larger rover. Capturing nature-tested capabilities from biology, such biomorphic explorers may possess animal-

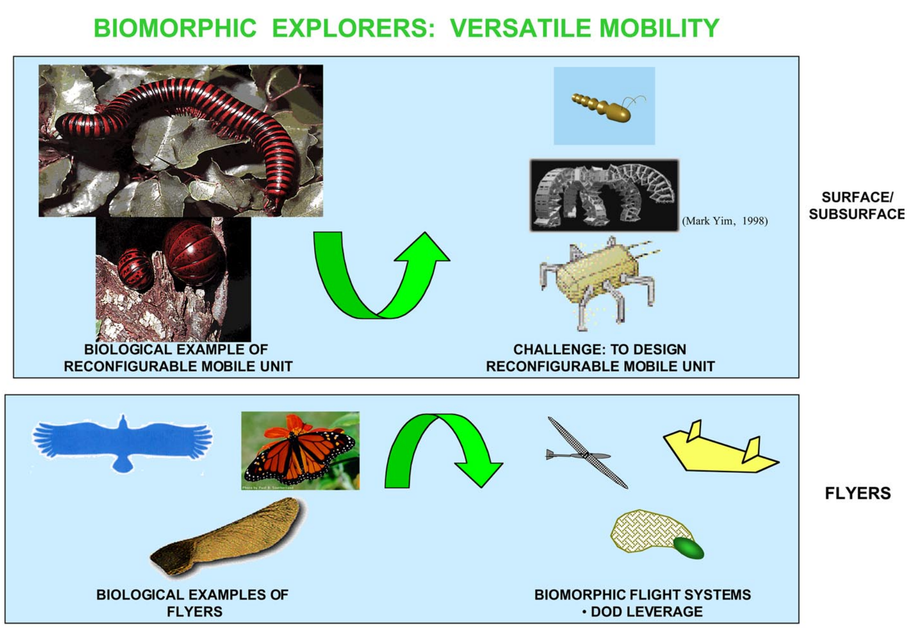

Figure 5. Reconfigurable mobile units

like mobility and adaptability. Their low cost and small size would make them ideal for hazardous or difficult site exploration, inspection, and testing. Their dedicated sensing functions and maneuverability would be valuable to scouting missions and sample acquisition from hard-to-reach places. Such biomorphic explorers would complement the capabilities of larger and relatively expensive exploration platforms/ modes (e.g., orbiters, landers, rovers, etc.). Biomorphic explorers can possess varied mobility modes, such as surface-roving, burrowing, hopping, climbing, hovering, or flying, for accomplishing surface, subsurface, and aerial exploration. Preprogrammed for a specific function and spread over the exploration site, they could serve as intelligent, downlink-only beacons that autonomously look for objects of interest. In a hierarchical organization, these biomorphic explorers would report their findings to a next-higher level of exploration (say, a large conventional rover) in the vicinity. This approach would allow more widespread and affordable exploration at lower cost and risk by combining a fast rover to cover long distances with the deployment along its route of numerous biomorphic explorers for in-situ sensing and local sample analysis/ acquisition. Sections VI through IX detail a few cooperative exploration scenarios enabled by the use of biomorphic explorers.

IV. Biomorphic Surface/Subsurface Systems

Multiterrain Biomorphic Explorer

The multiterrain biomorphic explorer utilizes bio-inspired sensor fusion and processing. Current wheeled mobility mechanisms are generally designed for, and therefore limited to, only preselected terrain conditions. Even with complex suspension mechanisms, wheels can typically negotiate (Wilcox et al. 1996) obstacles no more than about twice the wheel diameter. Furthermore, complex drive/transmission mechanisms make them more vulnerable. On the other hand, biologically inspired, alternative mobility mechanisms offer more adaptability to various terrain conditions according to LaBerbara 1983 and Gould 1981. The demonstration of biomorphic controls is a crucial task that, if successfully accomplished, will open up the potential of realizing application-specific biomorphic explorers and, hence, a new paradigm in mobile robotics.

The conceptual design (Thakoor and Kennedy 1998; Thakoor et al. 1997) of a multiterrain biomorphic explorer, as shown in Figure 6, consists of a multilegged robot capable of identifying its environmental condition or situation and adaptively changing its mobility mode to suit the prevailing or impending situation. For example, if the terrain changes from hard and rocky to swampy, slushy ground, then the explorer changes from a small footprint, pogo-stick-type mode to a duck-feet-like, wide-footprint mode.

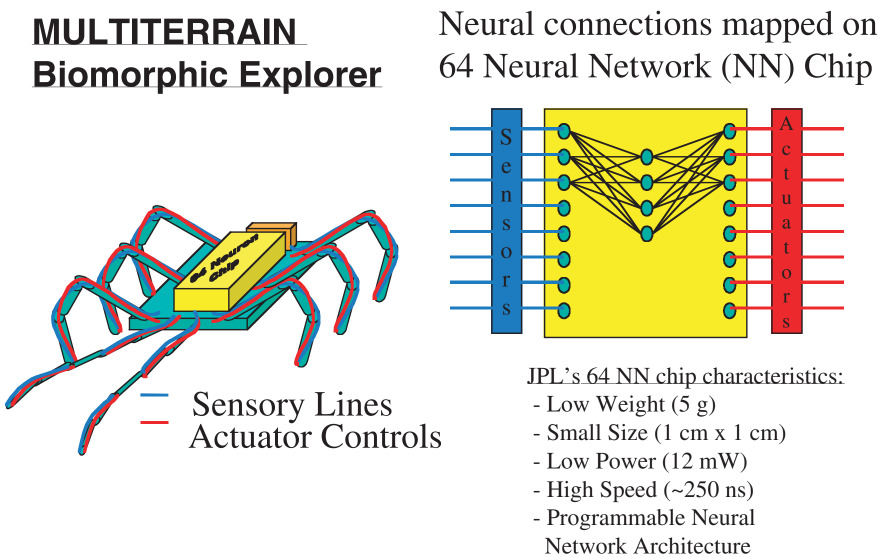

Figure 6. Crawler utilizing biomorphic control; biomorphic control operational schematic

Figure 7 shows the operational schematic of the biomorphic strategy controller, which utilizes multiple sensory inputs and generates the best-suited output choice of mobility mode, both in terms of the reconfigurable unit that is used and the mobility parameters that need to be used.

The worm robot conceptual design (Thakoor, Kennedy, and Quillin 1997) illustrated in the top section of Figure 5 is inspired by the techniques used by earthworms and inchworms.

The mobile entity is composed of a series of modules, where each module is capable of contracting or expanding and has anchors at each end. A module anchors at its back end and expands fully, then it de-anchors the back end and anchors the front end, then contracts again and re-anchors the back end. This wave of contraction/expansion and anchoring/de-anchoring proceeds continuously to achieve forward motion. As was illustrated in an earlier animation (Gorjian and Thakoor 1998), such a worm would be capable of burrowing in sandy soil and entering narrow cracks in rocks for obtaining pristine samples from such hard-to-reach places.

V. BIOMORPHIC FLIGHT SYSTEMS. These flight systems are a subclass of biomorphic explorers. Nature provides the ultimate example of alternative configurations (Shenstone 1968) to solve the problems of flight. Every flight entity, be it an insect or a seed, is uniquely different and each is optimally adapted (Ennos 1989; Norberg 1972) to its specific niche—literally adapted to its mission in life. Similarly, with aerial creations ranging from gossamer-light human-powered aircraft to the tons of metal of a supersonic jet or the complexity of a helicopter, each is

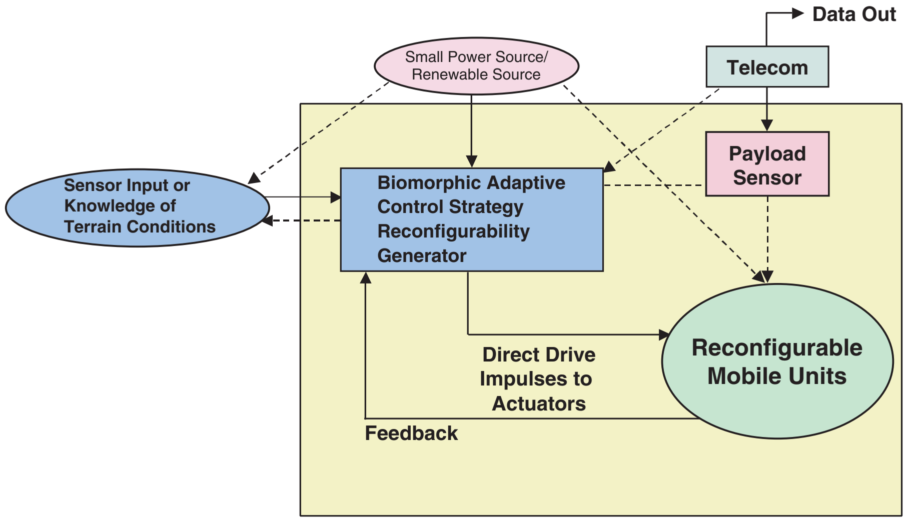

Figure 7. Biomorphic explorer control schematic

also refined for its specific, intended purpose. Biomorphic flight systems could follow the same trend. A number of different modes of flight and configurations could be developed, each of which would be optimized for achieving a particular combination of design parameters in accordance with varied, yet specific, applications or science needs; thus providing solutions to new endeavors of exploration.

A new idea (Norberg 1973; Sipe and Linnerooth 1995; Yasuda and Azuma 1997; Thakoor and Miralles 1999) that holds promise for a more robust and compact alternative to the parachute for small payloads is inspired by the plant world, particularly the techniques plants use to disperse seeds. Soaring birds (e.g., frigate birds, albatross, and hawks) use wind currents to stay aloft for hours, or even days, using little power to search for food or travel great distances. Migrating insects such as Monarch butterflies (Gibo 1981; Brodsky and Vorob'ev 1991) exhibit soaring in spite of their small size. It is well observed and documented that the Monarch migrates all the way from Canada to Mexico. Biomorphic flyer concepts can be envisioned to take advantage of the same kinds of rising air currents found on certain planets/planet satellites to stay aloft for periods of time while conducting meteorological and geological surveys. Gliders (Thakoor and Miralles 1999) using this type of natural flight mechanism have greater mobility and far superior directional control than balloons, are much lower in mass (and higher in payload fraction than balloons or powered air vehicles), and in suitable atmospheric conditions can stay aloft longer than powered craft.

Deployed in large numbers, these flight systems could substantially enhance science return. Unlike other exploration platforms, the flight systems can cover distances of several kilometers in a very short time, nearly independent of terrain. Compared to surface crawlers, biomorphic flight systems have the potential for substantially higher mobility (in speed, range, and terrain independence). Biomorphic flight systems can even be made to deliver other biomorphic explorers to target sites, greatly extending the utility of those explorers. These flight systems, with their ability to land relatively softly, have the advantage of being a good means for distribution of payload.

Three general overlapping volume-based categories ('a' = 1 to 20 cc, 'b' = 10 to 200 cc, 'c' = 100 to 2000 cc) were defined earlier, within the Microexplorers study (Thakoor 1997). In addition to their size and volume classifications, these flight systems may be categorized further by vehicle class, flight regime, deployment, propulsion, and method of control. A few examples within these classifications are given below:

Class:	glider, powered, boost glider, balloon, helicopter, blimp, or autorotating seed wing
Flight regime:	subsonic, transonic, or supersonic
Deployment:	launch from surface, entry probe, orbiter, or from larger atmospheric platform
Propulsion:	propeller, flapping, rocket, or unpowered
Control:	autonomous, telerobotic, biomorphic controls, or uncontrolled

VI. COOPERATIVE MISSION SCENARIOS FOR EXPLORATION: BIOMORPHIC MISSIONS. Cooperative mission scenarios utilizing a combination of biomorphic explorers with versatile mobility modes are conceptualized in this section. Cooperative exploration with a lander, a rover, and a multitude of inexpensive biomorphic explorers would allow comprehensive exploration at a low cost and with broad spatial coverage. For orbiters, landers, rovers, and astronaut missions, flight systems in particular provide a means for exploring beyond the visual range of on-board cameras. They aid in identifying targets of scientific interest and determining optimal pathways to those targets. In the case of an orbiter or entry probe, for example, a large number of gliders or seed wing pod flyers spread over a general region of interest could return in-situ measurements to augment science from images taken from space.

Payloads can range from small cameras to specialized science experiments designed to measure geophysical, chemical, or atmospheric properties. The biomorphic flight system itself can be designed to seek out features of interest, crash at the target site, and then act as a homing beacon for a lander or rovers that would later conduct further experiments. For data return, multiple communication options such as daisy chain, beacon, global broadcast, and/or hierarchical organization would be practical.

Biomorphic missions are therefore cooperative missions that make synergistic use of existing or conventional surface and aerial assets along with biomorphic robotic systems. Specific science objectives targeted for these missions include close-up imaging for identifying hazards and slopes, assessing sample return potential of target geological sites, atmospheric information gathering by distributed multiple-site measurements, and deployment of surface payloads, such as instruments, biomorphic surface systems, or surface experiments. Two biomorphic missions pertinent to NASA exploration goals are described and illustrated in Figures 8 and 9. Since Mars missions are of great interest, these scenarios have been influenced in their illustration by information gathered on recent (Raeburn 1998; Godwin 2000) Mars missions.

Cooperative Lander/Rover: Biomorphic Explorers Mission

When exploring a new terrestrial or planetary surface in-situ, the challenge is to be able to quickly survey and select the sites of interest. Imaging done from orbiters currently allows broad coverage but at limited spatial resolution: ~ 60 cm–1 m/pixel. Descent imaging may provide a context for landed vehicles; however, it is not broad enough to plan exploration paths/areas for a rover or to characterize potential sample return sites. Images taken from surface-sited landers/rovers with masts ~1 to 2 meters high do not cover the surroundings adequately far from their location. Coverage of a large area is warranted, and close up imaging (~5–10 cm resolution) and in-situ imaging at even greater resolutions is desired. The essential mid-range, 50- to 1000-m altitude perspective, is as yet uncovered and is an essential science need. Imaging

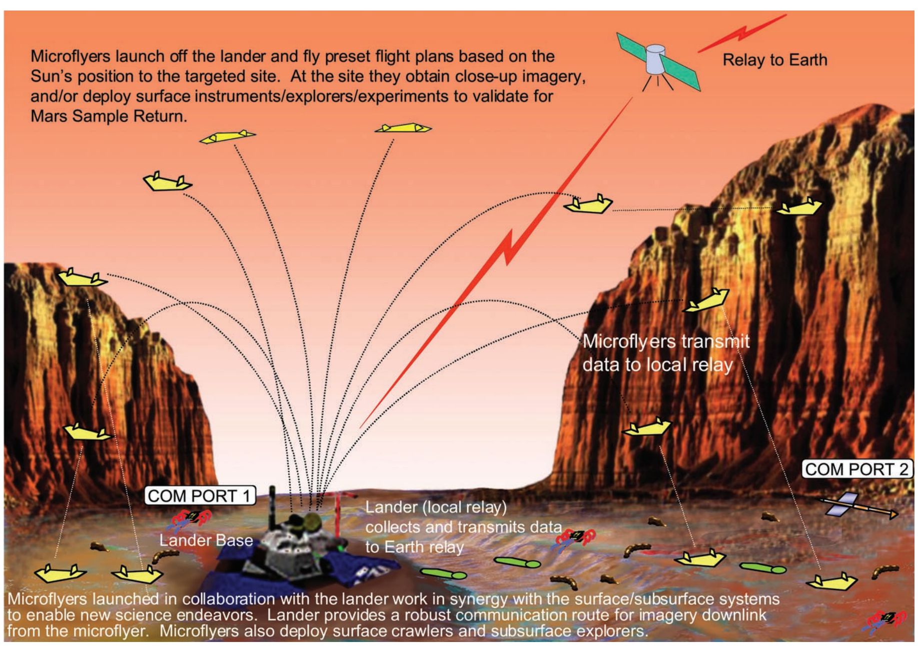

Figure 8. Biomorphic mission: Cooperative Lander/Rover—biomorphic explorers

from this mid-range is required to obtain details of surface features/ topography, particularly to identify hazards and slopes for a successful rover mission. For a planet with an atmosphere, such as Mars, flyers carrying cameras can provide the larger-scale visibility at the required spatial resolution within the context of orbiter and/or descent imaging. A cooperative lander-rover-biomorphic explorers mission is therefore suggested and illustrated in Figure 8.

The mission (Thakoor and Martin 1999) objective is to perform close-up imaging of 'over-the-horizon' terrain and perform surface measurements for site selection and sample return reconnaissance. A specific objective is to obtain samples from potential exobiology sites and areas of geological interest on Mars. Valles Marineris is a potentially favored landing site because, by comparison with our Grand Canyon here on Earth, it is expected to be potentially rich in geological data in one single site. Additionally, if accessible, it will be possible to sample the whole section from top to bottom from an individual landing site. Bridger 1987 has proposed a study of the entire stratigraphic column exposed along the canyon wall. Lucchita 1987 has described Valles Marineris as an optimum science sample site. A lander equipped with a large rover (and ascent vehicle) or a large rover/lander touches down in the Valles Marineris roughly 10–100 km from an area of potential exobiological significance, including fault zones with exposed geological features and eroded canyon walls with exposed sedimentary layers. The lander or rover/lander is targeted in a relatively flat area (possibly devoid of interesting samples) to minimize risk in landing. The rover is designed for traversing rugged terrain and is equipped with an arsenal of scientific experiments, including the ability to obtain and store samples. The rover is heavily instrumented and therefore quite expensive and by no means expendable. However, there is always a risk of damage or loss in negotiating the rugged terrain. Thus, some knowledge of the terrain and locations of scientific targets can significantly reduce mission risk and improve sample collection efficiency. After shedding the protective gear and making necessary deployments, a javelin is launched from the lander, and travels between 500 m and 1 km. The javelin and lander begin emitting low-power RF signals, which will be used for radio navigation by the microflyers and other explorers. The canyons in the foothills of the Valles Marineris are varied, some with steep walls and rubble at the base; others are filled with wind-blown sand. Many canyons end abruptly after a short distance or become impassable due to rock slides. From its vantage point in the valley, the lander cannot determine the location of ideal science targets or the best paths to reach them. The rover could waste a tremendous amount of time searching for a suitable path and going down dead ends.

The lander or rover/lander is equipped with several microflyers. A launching mechanism is used to launch the microflyer towards the target site specifying a flight heading. Launch energy could be provided by a small solid rocket, pneumatic thrust, compressed in-situ resource gas launch, a spring, electrically powered launch, or a mechanism combining two or more of the stated techniques. The communication range is kept small (< 10 km), and the lander local relay base is always available. Different flight paths over different terrains of interest are followed by the different flyers. Surface imagery is obtained using miniature camera systems on the flyers. The microflyer relays imagery/meteorological data to the lander and, after landing, conducts/deploys a surface experiment and acts as a radio beacon to indicate the selected site.

This particular flyer also can be equipped with the logic needed to identify specific features that may signify an area of scientific interest. The flyer then makes a decision to terminate the flight when its sensor identifies a potential exobiological site. Its small size, low mass, and rugged design enable it to survive the impact with the ground. It then deploys a small science experiment with a chemical or pyrotechnic device and a "sniffer" to determine the presence of some trace element. Perhaps this experiment might even burrow several centimeters below the surface. The flyer then uses its remaining power and the power from a small photovoltaic cell to periodically transmit the results of its tests. This transmission also acts as a beacon.

The lander receives the images and beacon signals transmitted by the flyers and relays them to the science team and mission planners on Earth. Several other flyers are launched in succession, each on its own radial, and the images and data are collected and sent to the project team. Based on this data, the project team identifies target sites with the greatest science potential, and suitable pathways are mapped.

The rover then begins its mission, with numerous radio beacons aiding in navigation. Along the way, the rover finds itself unable to negotiate a way around some fallen rock and debris. The rover itself carries several flyers, designed for slow flight, and deploys one to survey the area. Also, the rover could carry several microflyers to allow functional subdivision. Using the rover as a beacon, the flyer takes images of the rover and surrounding area while sending the images back to the lander. Mission planners are able to use the information to plan an effective route, not to mention getting an image of the rover in a rugged remote location for the media. Little time is wasted and the risk is minimized. The rover executes its mission plan and obtains samples from several sites before returning to the lander and depositing the samples into the ascent vehicle. Microflyers launched from the lander or rover/lander could also disperse other biomorphic multiterrain surface or subsurface explorers. These tiny multiterrain explorers could be the climbing type or rapelling type, scaling the columns of Valles Marineris and obtaining

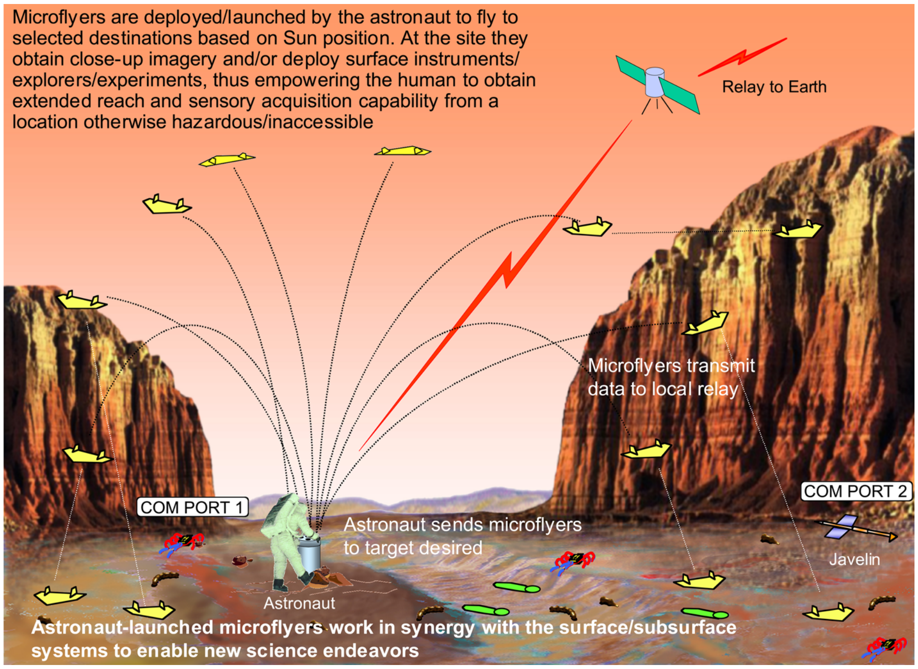

Figure 9. Biomorphic mission: Astronaut-launched microflyers

close-up stratigraphic data. Microflyers could also be used to send the samples back to the lander for collection. In this reconnaissance role, the microflyers maximize the effectiveness of the larger rover/lander.

If the feasibility of this approach can be verified, use of surface-launched imaging microflyers would be a powerful option for enhancing the public interest and science return from a Mars '05 and/or '07 rover or sample return mission. Use of flyers at Mars would have great public appeal. The unique perspective of the images acquired from such flyers will excite the public as well as provide valuable mission support. The chances of selecting the most interesting sites for visitation by a rover within the limited time and resources of the mission could be increased dramatically. Identification of the most interesting specimens to be collected as returned samples could be enabled over a much wider area than could be done from the rover directly. In these ways, the scientific return from a rover mission would be increased. Further development of a planetary flyer capability will also have potential application to future missions to other planets and satellites with atmospheres, such as Venus, Jupiter, Saturn, and Titan.

Biomorphic Missions for Human Exploration and Development of Space

Biomorphic explorers can be deployed/launched by the astronaut to selected destinations. Solar navigation is utilized by the launched biomorphic explorer. At the targeted site, the explorers obtain close-up imagery and can further deploy surface instruments or biomorphic surface explorers. Thus, the human (astronaut) is empowered to obtain extended reach and extended sensory acquisition capability from a location that otherwise would be inaccessible or hazardous to access. Such a mission is illustrated in Figure 9 for human exploration and development of space.

Biomorphic explorers could also assist with the building, repair, and periodic maintenance inspection of future human habitats on the Moon or Mars.

VII. Plant-Inspired Biomorphic Techniques for Dispersal of Payloads. This section presents a few of the envisioned biomorphic missions for distribution of instruments/biomorphic surface systems (payload) using ideas (Guries and Nordheim 1984; Peroni 1994; Greene and Johnson 1992) inspired by seed dispersal in the plant world, such as dandelions and seed wing pods. These mission ideas are illustrated in Figures 10, 11, and 12.

VIII. Biomorphic Missions Utilizing Lander Local Relay. A high-altitude near-synchronous orbit providing long-dwell service to any point on Mars is necessary (or preferable) for success in the type of mission shown in Figure 13. While our telecom infrastructure is still in its infancy, a cooperative mission using a lander/rover as a robust local relay can enable, even with existing low-altitude orbiters, an imagery mission with biomorphic flyers as shown in Figure 14.

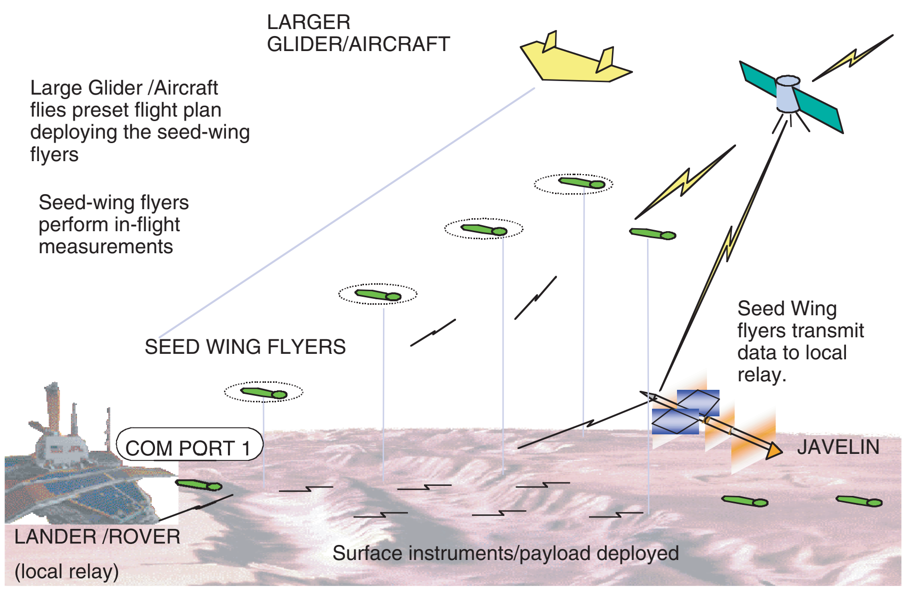

Figure 10. Deployment scenario where the seed wings are aerially deployed by a glider/aircraft

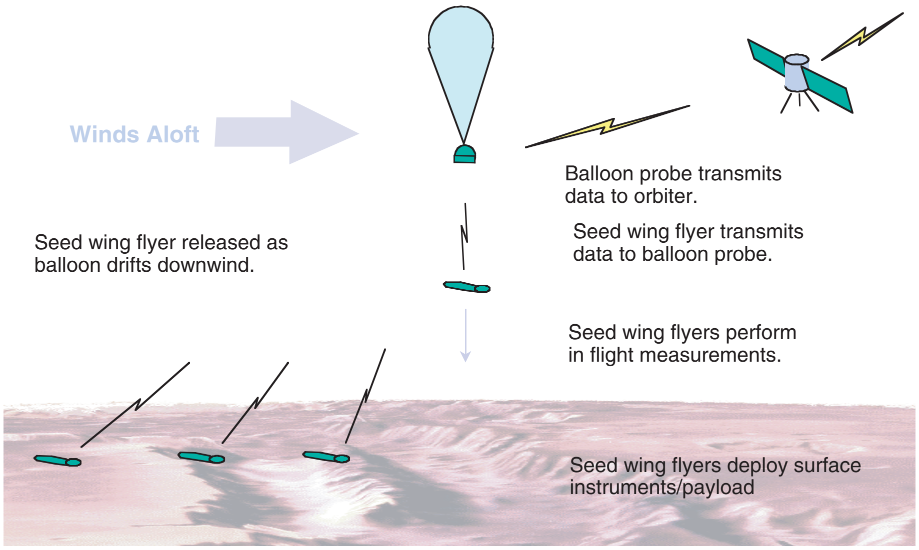

Figure 11. Deployment scenario where the seed wings are aerially deployed by a balloon

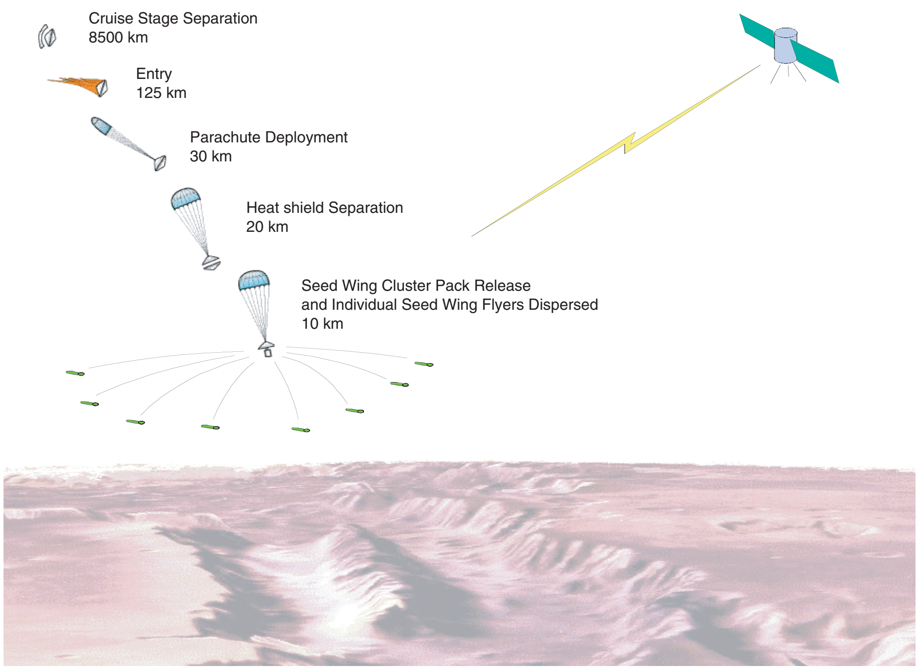

Figure 12. Deployment scenario where the seed wing cluster is aerially deployed directly after initial slow-down

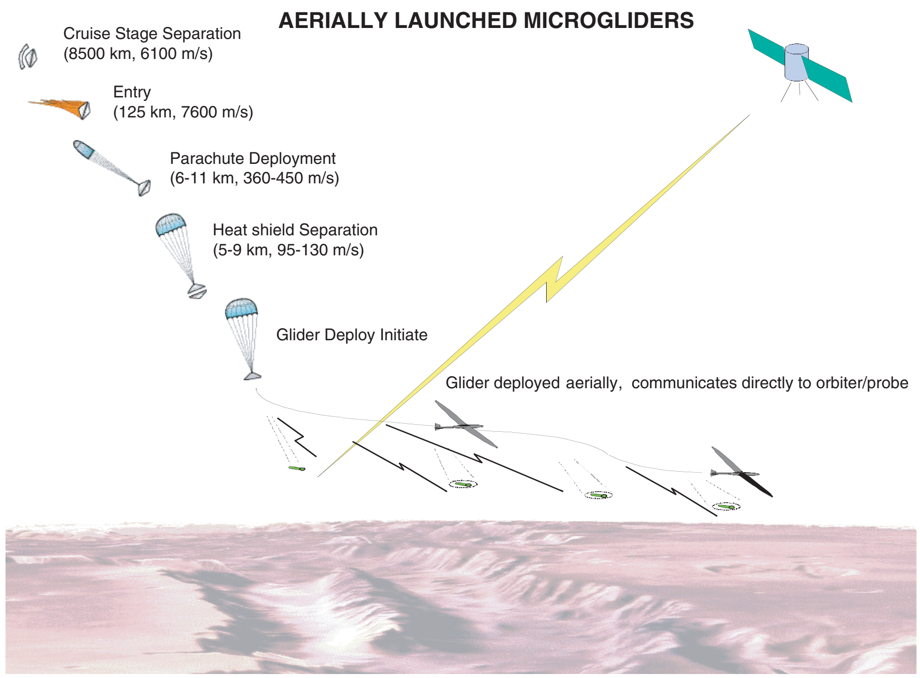

Figure 13. Aerially deployed microgliders need telecom infrastructure for viable operation

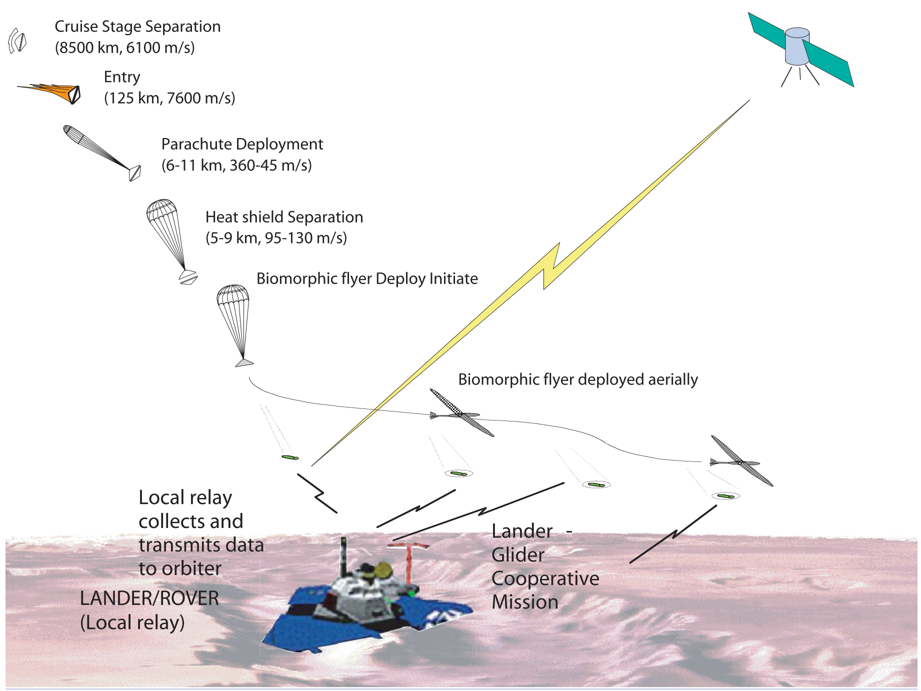

Figure 14. Cooperative use of a lander/probe provides a robust local telecom relay for data downlink from the biomorphic flyer

IX. BIOMORPHIC MISSIONS: A FEW FUNCTIONAL SAMPLES. The following mission concepts represent a small sample of the many potential mission scenarios possible with biomorphic exploration systems. Each scenario, also described elsewhere (Thakoor 1998b), is written in a stand-alone fashion. Some of the same pertinent issues are addressed independently for each case.

Orbiter-Based Seed Wing Pod Flyers for In-Situ Measurement

Motivation

The mission objective is to augment orbiter image data with in-situ surface measurements. The information obtained will also assist in identifying suitable lander sites for future missions. Orbiters have been used very successfully to obtain large-scale geological and meteorological data. Although the information is extremely useful, image resolution is limited to several meters in scale due to practical constraints. Furthermore, in-situ compositional measurements at specific sites of interest can significantly add to the science return and aid in future mission planning.

Mission description

This mission is illustrated in Figure 12. After orbiting a planet or satellite (e.g., Mars, Titan) and sending images to Earth for several weeks, the science team identifies several regions of geological interest. One of three entry vehicles is launched from the orbiter so that the payload is released over a target area. The entry vehicle contains 10–20 small seed wing flyers, each equipped with a small surface probe, chemical experiment, camera or another specialized biomorphic/microexplorer. Seed wing pods are a very compact way of dispersing experiments and microexplorers over a broad area.

At an altitude of about 15 km, the entry vehicle begins a controlled release of the seed wing flyers, which autorotate to the surface. The entry vehicle will traverse 50 to 100 km during the course of releasing the seed wings. A straight, circular, or intelligent flight plan may be used. Meteorological information on weather patterns will be utilized to select the timing of release of the seed wings in this mission to maximize the science return.

After the seed wings have landed, each conducts a surface experiment that may consist of a surface probe and/or a chemical test, which analyzes for the presence of key trace elements. Next, the orbiter emits a signal initiating communications. The identified seed wing then transmits the results of its experiment. No return indicates a failure of that specific seed wing or that the signal is obscured by terrain, so another attempt to communicate should be made from a different aspect angle. The orbiter receives the transmissions and locates each seed wing using a phased array antenna.

Two other regions of interest may be explored in the same manner with the remaining two entry vehicles and seed wing pods.

Impact on orbiter mission

Mass—The total mass of the three entry vehicles and a total of about 50 seed wing pod flyers is on the order of 9 kg (60 g per seed wing, plus 2 kg per entry vehicle @ 50% payload mass fraction). In addition, the orbiter will have a phased array antenna with ~1 kg mass.

Development status—The seed wing is a passive entry device much like a parachute (only simpler). Biomorphic control of seed wing descent is a significant concept for further development and will impact the usefulness of seed-wing flyers. This is an effort to influence the direction of descent by periodic movement of a control surface on the wing portion. For example, a simple wing structural element made of advanced piezo-polymeric composite actuators could play a dual role as a structural member as well as an active control element (when activated), altering the lift characteristics for a fraction of one rotation. The signal to drive the structural element would be generated by the measurement of sunlight on the upper payload surface. This signal would normally vary with rotation due to changing Sun angle. Detection of a certain part of that periodic signal would be programmed to activate the change in wing shape. Thus, the seed wing would tend to move in a consistent pattern relative to the Sun direction. Individual seed wings in an ensemble could be programmed to have varying solar response patterns, ensuring that the group travels away from each other, for maximum dispersion in the landing location. The small scale, simplicity, and economies of scale with volume production suggest that this concept would be very low in cost and could be ready for deployment in a minimum of time. The entry vehicle development cost and schedule will most likely be dependent on the complexity of its flight profile. The simplest and cheapest will be a passively stable entry vehicle capable of gliding without controls or active stabilization and will most likely fly in a large circular flight path.

Risk—It is unlikely that incorporating this concept will in any way jeopardize the primary orbiter mission. Any entry vehicle related failure could be partly mitigated by triggering dispersal of all the seed wings before the entry vehicle impacts the surface. Some seed wings are expected to fail with little impact on the overall results. Improper placement of the seed wings will result in acquiring data for a site other than the preferred site but still some data would be acquired from an alternate site.

Benefit—The benefits include in-situ measurement of the mineralogical or chemical composition of soil at or near the surface to correlate with orbiter images. Key findings or validation of image data for use in selection of future lander sites would be valuable.

Orbiter-Based Biomorphic Gliders for In-Situ Measurement

Motivation

The mission objective is to augment orbiter image data with in-situ surface measurements and assist in identifying suitable lander sites for future missions. Orbiters have been used very successfully to obtain large-scale geological and meteorological data. Although the information is extremely useful, image resolution is limited to several meters in scale due to practical constraints. Furthermore, in-situ compositional measurements and higher resolution close-ups of specific sites of interest can significantly add to the science return and aid in future mission planning.

Mission description

Two possible versions of this mission are illustrated in Figures 13 and 14. After orbiting a planet or satellite (e.g., Mars or Titan) and sending images to Earth for several weeks, the science team identifies several regions of geological interest. One of three entry vehicle is launched from the orbiter so that the payload is released over the target area. The entry vehicle contains 25 or so small biomorphic gliders; each equipped with a small IR camera, surface probe, and a chemical experiment. At an altitude of about 12 km, the entry vehicle releases the gliders.

The gliders transition to flight and initially head out in more or less random directions. Each glider is equipped to identify several geological features of interest based on a hierarchical list and using the IR sensor image. A high priority target feature is selected within its field of view and glide performance. The flight path is adjusted to intercept the target feature. (This is the search, identify, and target mode.)

En route, each glider in turn emits a weak signal identifying the type of feature targeted and the number of other feature classes identified within its glide range. Each glider also receives the signals from the gliders near it. Based on this information, gliders with a large number of neighbors targeting the same feature type have the option of selecting a different feature or adjusting course to seek new features, thus ensuring maximum dispersal and variation of science return.

After the gliders have landed, the orbiter emits a signal initiating communications with each of the gliders. The identified glider then transmits the last camera images for a close-up view of the surface. No return indicates a failure of that specific glider or that the signal is obscured by terrain. Another attempt to communicate should be made from a different aspect angle. While on the surface, the glider also conducts a surface experiment that may consist of a surface probe and a chemical test, which is analyzed for presence of key trace elements. This data is then included in the transmission. The orbiter receives the glider transmissions and locates each using a phased array antenna.

Two other regions of interest may be explored in the same manner with the remaining entry vehicles.

Impact on orbiter mission

Mass—The total mass of the 75 gliders and three entry vehicles is 12 kg (assuming 100 g per glider plus 1.5 kg per entry vehicle). In addition, the orbiter will have a phased array antenna with ~1 kg mass.

Development status—The glider is relatively simple due to the lack of a propulsion system. Also, flight performance and range is directly related to lift/drag and release altitude. As compared to powered flyers, the glider is relatively insensitive to mass and other design complexities, which make the glider a fairly low-risk development effort. Most technologies for flight-related systems exist or are being proven through micro air vehicle (MAV) development. Micro-electro-mechanical-system (MEMS) technologies are now being developed for chemical sensing and navigational aids, which may be adapted for this application. The very small IR camera and biomorphic/multi-agent controls are likely the most difficult developments.

Risk—It is unlikely that incorporating this concept will in any way jeopardize the primary orbiter mission.

Benefit—In-situ measurement of the mineralogical or chemical composition of soil at or near the surface can be used to correlate with orbiter images. Key findings and near-surface image data will be extremely valuable in selection of future lander sites.

Cooperative Lander-Rover-Biomorphic Flyers Mission

This mission has been described in detail in Section V.

Impact on lander mission

Mass—Assuming the lander is carrying 12 microflyers, the total mass of the 12 flyers can range from 1.2 to 6 kg (assuming 100–500 g per flyer). Correspondingly, an additional 1–6 kg would be needed for the launcher and communications instruments.

Development status—Envisioned in this study to be launched from the lander, the microflyer could be a boosted glider design. For Mars with its thin atmosphere (~ 1/100th of Earth's), a single- or multiple-stage rocket booster payload package, almost like a dart, is envisioned (Thakoor 2000a; Small 2000). The number of rocket stages (and hence the mass of the microflyers) will be determined by the range required for the mission. An electrically powered microflyer is another possibility (Dornheim 1998). DoD/Industry-sponsored developments in each of these areas are emerging, including boosted microgliders (Small 2000) and electrically powered microflyers (Dornheim 1998; Harris, Knutsen, and Devine 1999; Foch 1999). Modifying the design for such a lander-launchable microflyer for Mars ambient is the major challenging step yet requiring development. Most technologies for flight-related systems exist or are being proven through ongoing MAV development. MEMS technologies are now being developed for chemical sensing and navigational aids that may be adapted for this application. A very-small IR camera and communications equipment providing high data rates with minimal power are other outstanding developments required. The lander/rover in this mission scenario provide a robust telecom local relay to downlink the data to Earth via the existing Mars orbiter. This mission could therefore be achieved relatively easily without the need for additional telecom infrastructure. Thus, a scouting mission of this type is quite possible in the 2005 time frame, assuming a concerted start of development at the time of writing of this paper. Further on, by 2007–2009, dispersal of surface instruments and other multiterrain biomorphic surface/subsurface systems by the microflyers could enable a thorough investigation of the stratigraphy of columns in Valles Marineris. This could be accomplished using locally deployed biomorphic explorers of the climbing or rapelling kind. A fetch-and-return of samples capability could be obtained by 2011. Beyond 2011, a closely related scenario described in Section 6 could be realized as an enabling aid to the human exploration and development of space.

Risk—Incorporating this concept will not in any way jeopardize the primary lander mission. In fact, the flyers in this case are used to minimize mission risk and enable new science endeavors.

Benefit—A scouting mission to map out the regions of interest and pathways of interest can be enabled by such a cooperative biomorphic mission implementation. In-situ measurements can be made of the mineralogical or chemical composition of soil at or near the surface over a broader area than the lander/rover will be able to cover. Key findings and near-surface image data will be extremely valuable in lander/rover pathway selection and planning for maximum science return from the mission. Dispersal of payload and a fetch and return of samples capability are other longer term benefits of such mission developments.

Biomorphic Gliders for Sample Return Mission Reconnaissance

<u>Motivation</u>

The mission objective is to obtain samples from potential exobiology sites and areas of geological interest.

<u>Mission description</u>

A lander equipped with a large rover and an ascent vehicle lands in the Valles Marineris, roughly 10 km from an area exhibiting potential exobiological significance, fault zones with exposed geological features, and eroded canyon walls with exposed sedimentary layers. The lander is targeted in a relatively flat area (devoid of interesting samples) to minimize risk in landing. The rover is designed for traversing rugged terrain and is equipped with an arsenal of scientific experiments including the ability to collect samples for return. Unfortunately, the rover is expected to have a limited life and there is always a risk of damage or loss. Therefore, some knowledge of the terrain and locations of scientific targets can significantly reduce mission risk.

Gliders, equipped with a miniature camera and, possibly, a small IR detector and a simple surface experiment may be deployed to obtain intelligence for targeting specific sites of scientific interest and for planning rover pathways. The lander would most likely have to be in place within the Valles Marineris before glider deployment to minimize the transmit power required.

Perhaps as many as 50 small gliders are stored inside a simple, passively stable entry vehicle. The entry vehicle would begin releasing the gliders near the top of the canyon walls at an altitude of about 14 km so they can glide down toward the bottom of the canyon at a nearly constant altitude above the surface. Each glider will use a small camera to take images of the terrain below and transmit the images to the lander, which will relay them to Earth via the orbiter. After landing, each glider may conduct a simple experiment or deploy another biomorphic explorer, which transmits results to the lander while acting as a radio beacon. Each glider would be programmed for a specific flight trajectory based on navigation using the Sun. Thus, the images may be geologically referenced using the beacon signal location. The project team uses the information to identify target sites with the greatest science potential and to map suitable pathways for the rover. The rover is then deployed having a mission plan and numerous radio beacons to aid in navigation.

<u>Impact on lander mission</u>

Mass—The total mass of the 50 gliders and entry vehicle is about 10 kg (assuming 100 g per glider plus 5 kg for the entry vehicle).

Development cost and schedule—The glider is relatively simple because a propulsion system is not required. Flight performance and range is directly related to lift/drag and release altitude. The glider would be a low-cost and fairly low-risk development effort. Most technologies for flight-related systems exist or are being proven through DoD/Industry-sponsored MAV development. MEMS technologies are now being developed for chemical sensing and navigational aids, which may be adapted for this application. The very-small IR camera and communications equipment with multiple data streams, high data rate, and high power efficiency are other developments needed.

Risk—It is unlikely that incorporating this concept will in any way jeopardize the primary lander mission. In fact, the flyers in this case are used to minimize mission risk.

Benefit—The benefits include in-situ measurements of the mineralogical or chemical composition of soil at or near the surface over a broader area than the rover will be able to cover. Key findings and near-surface image data will be extremely valuable in rover pathway selection and planning for maximum return.

Biomorphic Gliders for Payload Deployment to the Polar Ice Cap

Motivation

The mission objective here is to obtain historical climatology data on Mars through in-situ compositional measurements, analogous to core samples, of the ice cap taken at various depths below the surface. The experiments are to be conducted at ten sites over a broad area (without specific targeting) to gain information on ice uniformity. The project is to be carried out as a piggyback micromission and the hardware is to be contained within one entry vehicle.

Mission description

During approach to Mars, the entry vehicle is released toward the polar ice cap. Gliders may be used to obtain images of the ice layers at the edges of the ice sheet. Contained inside the entry vehicle are 10 biomorphic gliders carrying one experiment each. At 15 km above the surface, the entry vehicle releases/disperses these gliders. The gliders are simple, passively stable, free-flight (uncontrolled) platforms that glide in random directions traveling roughly 6 km forward for every 1 km lost in altitude. The total dispersal pattern for the 10 gliders will be roughly 100 km in diameter. Once on the surface, the glider shape is designed to minimize the chance of becoming airborne once on the surface, perhaps aided by use of an anchor.

Each glider carries a biomorphic explorer designed to burrow through ice, snow, and soil using a combination of scraping and heat while pulling debris around itself and applying downward pressure with its limbs. Upon landing, the burrowers begin digging into the surface. If needed, power and communications with the spacecraft can be provided to the burrower by the glider via an umbilical cord, which is unwound as the burrower makes its progress. The glider is equipped with batteries, photovoltaic cells, and transmitter.

The limited light available for solar power implies that progress will be slow, but a simple spring-loaded panel with solar cells is released into a vertical orientation to maximize Sun exposure and capture reflected light from the surrounding ice. Burrowing will periodically need to be stopped to enable the solar cells to recharge the battery. Once deployment is complete, there are no moving parts on the surface that must endure the harsh polar environment. The batteries would utilize self-heating and good insulation to maintain reasonable performance.

The burrowers would carry narrow-band LEDs or other instrumentation to detect different ice layers and possibly to determine composition (H_2O or CO_2). Measurements and reports on progress (depth) would regularly be transmitted to the orbiter.

Impact on orbiter mission

Mass—The total mass of the 10 gliders, 10 burrowers, and the entry vehicle is about 3.5 kg (assuming 100 g per glider, 100 g per burrower, and 1.5 kg for the entry vehicle).

Development cost and schedule—The glider is relatively simple due to the lack of a propulsion system. Flight performance and range are directly related to lift/drag and release altitude. The glider would be a low-cost and fairly low-risk development effort. Most technologies for flight and burrower support-related systems exist or are being proven through MAV development. The burrower is likely to be the most expensive and risky development effort.

Risk—Use of multiple instruments and delivery vehicles helps to reduce mission risk significantly.

Benefit—In-situ measurements of the ice cap can be made over a broader area than a single lander will be able to cover.

X. OTHER POTENTIAL APPLICATIONS OF BIOMORPHIC MISSIONS. The earlier sections of this paper detailed cooperative scenarios relevant to planetary exploration. More generally, utilizing cooperative behaviors may be indicated in aspects of missions that are inherently distributed in space, time, or functionality. The advantages of distributed, cooperative exploration can include increased reliability and robustness (through redundancy), decreased task completion time (through parallelism), and decreased cost (through simpler individual explorer design). Also, a multitude of other applications exist in both the human exploration and development of space and in the terrestrial domain. A partial list of tasks that can be supported includes cleanup of hazardous waste, nuclear power plant decommissioning, search and rescue missions, construction, mining, automated manufacturing, industrial/household maintenance, security, surveillance, and reconnaissance.

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